

Geothermal energy use in hydrogen production: A review

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Summary

The major logics resulting in hydrogen production can be mentioned as fossil fuel depletion and climate change. In this way, hydrogen is produced with the help of numerous processes based on traditional and alternative energy resources like coal, natural gas, wind, solar, biomass, and geothermal energy. Over the past decade, the attention of research institutions and industry has been drawn to hydrogen, inspired by developments in renewable energies. Hydrogen production can be considered as an exceptional choice to make complete utilization of the renewable energy. Among diverse technologies, hydrogen production based on geothermal energy offers great promise. In this paper, initially a concise summary of present and advancing hydrogen production technologies is presented, and secondarily a comprehensive review of research associated with hydrogen production based on geothermal energy is provided. Thirdly, the process descriptions of geothermal-assisted hydrogen production coupled with its technical, economic, and environmental aspects are addressed. Finally, comparative assessments of costs and environmental aspects related to hydrogen production based on different energy sources have been performed. In accordance with the results, the geothermal-assisted hydrogen production cost based on electrolysis is competitively lower than other sources like wind, solar thermal coupled with natural gas, solar PV, and grid. Also, the same behavior can be seen for geothermal-assisted hydrogen production cost based on thermochemical process.

KEYWORDS

environmental impact, geothermal energy, hydrogen production, renewable energy, techno-economic analysis, thermodynamic analysis

1 | INTRODUCTION

The consumption of renewable energies is augmenting all over the world due to depletion of fossil fuels and emission of greenhouse gasses into the air as the result of their combustion.¹ In this way, technical and infrastructural developments are required in order to increase the pace of their utilization. One dominant issue associated with renewable energy sources can be considered as their

shortcoming to store the generated energy in an applicable approach.² This issue is not relevant for biomass due to the fact that the generated fuels from biomass like ethanol and biodiesel can be utilized at any moment. Nonetheless, the produced electricity from wind turbines, solar systems, and geothermal power cannot be stored for subsequent applications.^{3,4} Additionally, batteries cannot be considered as an applicable option on the condition of present technologies due to their actual restricted

capacity. Producing hydrogen from renewable energies can be mentioned as a feasible solution to obviate this issue.⁵⁻⁷ It is possible to store hydrogen and utilize it once it is generated. The hydrogen production based on renewable resources would be a favorable path toward a prospective hydrogen economy due to cost-effective and clean approach for producing hydrogen.⁸⁻¹¹ In countries with a plentiful quantity of geothermal energy, hydrogen production based on geothermal sources is becoming a primary energy sector.^{12,13} In this way, plenty of endeavors have focused on scientific research, technological development, and employment of modernization in hydrogen production.¹⁴⁻¹⁶ The usefulness of hydrogen production technologies relies primarily on innovations which exploit them more resourcefully on the condition of reducing adverse environmental impacts.

In order to attain a mature and fully developed hydrogen economy, it is necessary to provide hydrogen with improved methods from more suitable resources due to diverse applications (3S approach) such as the hydrogen storage and distribution purposes.¹⁷ In that matter, a fully developed hydrogen economy is considered essential in diminishing destructive environmental issues such as global warming as well providing future sustainable development with significant environmental, economic, and societal benefits.¹⁸ Beside greenhouse gas emissions, further disastrous emissions such as sulfur oxides, nitrogen oxides, and particulates causing smog¹⁹ can also be eradicated to mitigate global warming.²⁰ Another advantage of hydrogen utilization is decreasing the noise pollution by replacing fossil fuel in combustion processes among various sectors such as transportation, buildings, and the industry.²¹ In addition, energy security can be achieved by utilizing domestic, locally available, dependable, and viable energy and material sources for hydrogen production, distribution, storage, and end-use.²²

The fulfillment of achieving a fully developed hydrogen economy requires significant research and remarkable investment in hydrogen production systems to demonstrate hydrogen as a key component in market.²³ For this reason, the hydrogen production systems should be more efficient, economical, reliable, and safe which are suitable for large-scale and stationary systems. In that matter, a well-developed hydrogen infrastructure will be required since the current technology satisfy previous aims.²⁴ This can be achieved by enhancing the capacity of hydrogen production systems which consequently result in cost reduction as well as growing satisfaction of the public, industry, and the governments.

Some papers focused on reviewing techno-economic and environmental impacts of hydrogen production systems by using various energy sources.^{13,25-27} As an illustration, the best and the worst environmental

performance belong to thermal and biological choices, respectively.²⁵ Additionally, the lowest electricity price can be obtained by using geothermal energy which leads to cost-effective hydrogen production.²⁶ Also, new improvements in PEM water electrolysis containing affordable high-performance OER and HER electrolysis have been reviewed which results in commercially potential hydrogen production.²⁷ Additionally, an innovative concept for hydrogen production called 18S has been reviewed which indicated that renewable energies especially solar, hydro, and geothermal are able to assist in the novel hydrogen production systems.

Up until now, very limited review papers exist in the literature with the aim of presenting an extensive comparison among the most of the dominant clean energy technologies specifically for large-scale hydrogen production based on geothermal energy. For this reason, almost 200 peer-reviewed articles were taken into account in the preparation of this review paper and numerous geothermal-driven hydrogen technologies were comparatively assessed by their economics and environmental impact.

For this purpose, the aim of this article initially is to provide a concise summary of present and advancing hydrogen production technologies, and secondarily to present a comprehensive review of research associated with hydrogen production based on geothermal energy, which focused on thermodynamic, techno-economic analyses, and environmental impacts of geothermal-assisted hydrogen production. Finally, comparative assessments of costs and environmental aspects related to hydrogen production based on different energy sources have been performed.

2 | GEOTHERMAL ENERGY

Geothermal energy is a renewable source of energy which is stored as heat in the depth of the earth.^{28,29} This source of energy is originated from internal structural features of the earth.³⁰ One of the major restrictions toward geothermal energy utilization is the accessibility to these thermal resources.³¹ Since a vast amount of this energy is stored in deeper parts due to excavation limitations.³² However, in the accessible areas of the world where drilling is possible, this form of energy can be industrially employed.^{33,34} In order to utilize the geothermal energy, a heat transfer carrier is needed to transfer this thermal energy from the deeper layer to the ground surface.^{35,36} In general, this process is done in two stages, and two heat transfer mechanisms are involved. The heat is transferred through conduction heat transfer between hot rocks, and then through convective heat transfer, the

hot water is delivered to the surface.³⁷ A geothermal reservoir, Figure 1, is able to produce superheated steam or mixture of water and steam dependent on its hydrogeological features and the temperature gradients.³⁹ These reservoirs can be drilled and take advantage of their benefits based on the fluid's temperature and pressure.

Geothermal energy utilization can be considered as a zero-CO₂ energy source and in comparison to wind and solar has this potential to supply an approximately constant and stable load during the day.^{40,41} Based on the statistics, 82 countries benefit from direct use of geothermal energy, and 26 countries use this energy for power production (ie, 0.3% of the total world electricity was produced from geothermal energy in 2012).^{42,43} The leader countries of geothermal power production in the world are stated in Figure 2. The global geothermal applications are depicted in Figure 3.

Recently, the utilization of geothermal energy has been increased dramatically due to the scarcity of energy throughout the world. Geothermal energy can be used to generate heating and to produce electricity (power) and can also be utilized in cooling technologies. Geothermal sources are not following a general trend, and each source has its own characteristics (ie, temperature, location, and well depth, etc.). Therefore, a specific technology cannot be applied in all geothermal sources, and different approaches are required to be tested to bring about an acceptable achievement. The pioneer geothermal technologies for power production purposes are binary, dry steam, and flash steam. Geothermal power

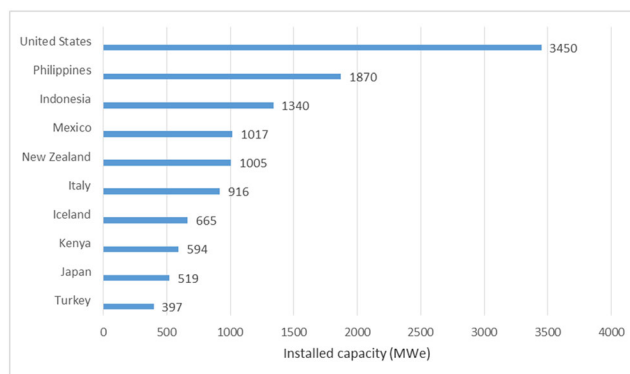


FIGURE 2 Leader countries in geothermal power production⁴⁴ [Colour figure can be viewed at wileyonlinelibrary.com]

production units have the potential to provide constant load, to be independent of climate changes, and to operate in high-efficiency mode.⁴⁵ Geothermal power plants are commonly employed in lands with high-temperature geothermal resources. Based on the Renewables 2018,⁴⁶ Figure 4, total global capacity of geothermal power production was 14 GW in 2017. It is expected to boost up this capacity up to 17 GW in 2023. Indonesia, Kenya, Philippines, and Turkey are predicted to be the leaders of geothermal power exploitation in the world by 2023.

Direct utilization of geothermal energy for heating utilities such as bathing, space heating, and agriculture, 45%, 34%, and 21%, respectively, is only used in a few number of countries, Figure 5.

In this way, plentiful investigations have been implemented to examine the use of geothermal energy.⁴⁷⁻⁴⁹ A

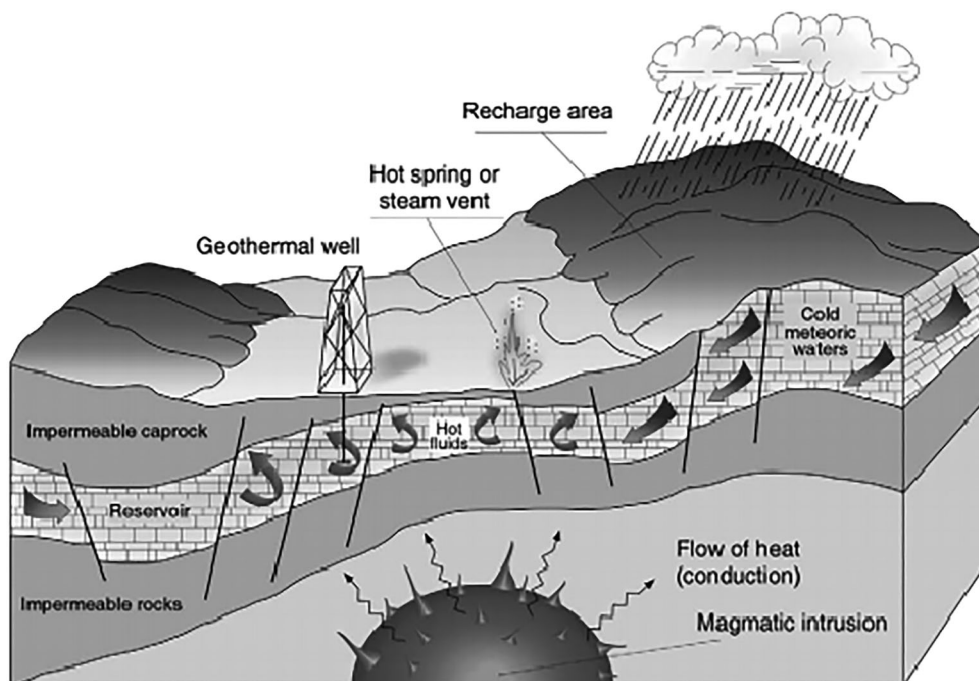


FIGURE 1 A schematic description of a geothermal steam field³⁸

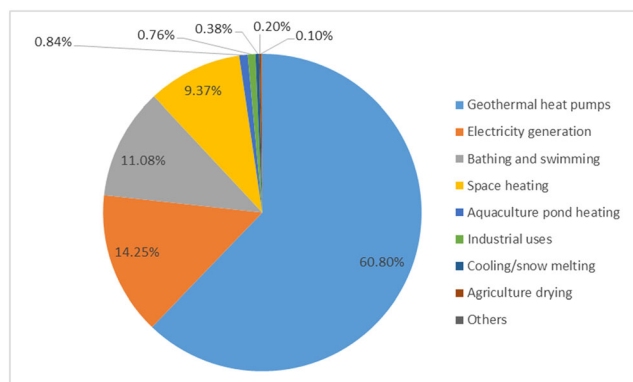


FIGURE 3 Geothermal energy applications⁴⁴ [Colour figure can be viewed at wileyonlinelibrary.com]

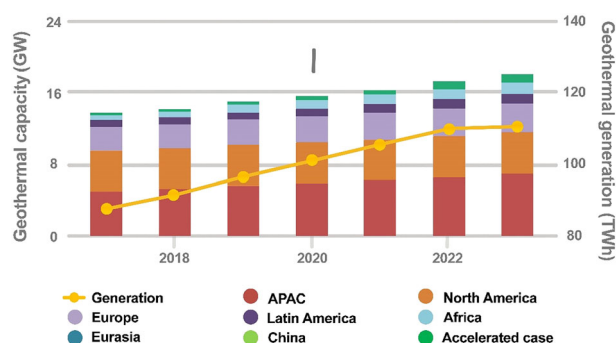


FIGURE 4 Geothermal power generation and cumulative capacity by region, 2017 to 2023⁴⁶ [Colour figure can be viewed at wileyonlinelibrary.com]

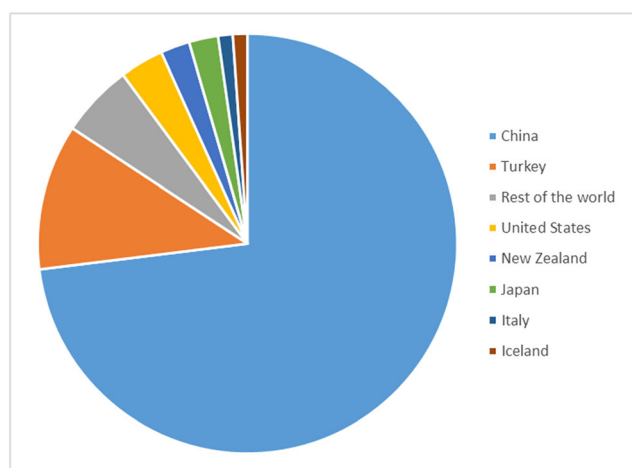


FIGURE 5 Geothermal direct use by country, 2016⁴⁶ [Colour figure can be viewed at wileyonlinelibrary.com]

study on the potential utilization of produced fluids in oil wells, which are active and located in the Gulf Coast states for power plants which have a binary cycle, was

presented by Wight and Bennett.⁵⁰ This paper introduced an approach to utilize water, which is geothermal fluid and heat exchanger in oil and gas wells which are abandoned. During the procedure, the mentioned wells are able to be utilized as geothermal sources. As a result, through a binary cycle, power can be generated. For the sake of measuring the parameters most favorable for this approach, the data obtained from 2500 wells in Texas, USA have been utilized.

One of the most significant consequences of the investigation can be enumerated as its feasibility to decrease the utilization of R-134a geothermal fluids has some unfavorable environmental issues. The requirement of augmenting mass flow rate is the increment of the depth of wells; however, the augmented depth leads to enhance the power output. It has been illustrated which abandoned oil and gas wells can be turned into power plant equipment work by geothermal sources of energy, with the help of applying this approach. The benefit associated with this approach can be mentioned that it is not dependent on normal geothermal fluids because the whole power is generated by the good resources. Also, it can be utilized for maximizing the generation capacity. New advances in geothermal systems are indebted to various novel ideas in regard to working fluid in geothermal systems. In that matter, further investigations are addressed to this subject in recent years. Chen et al⁵¹ carried out a three-dimensional numerical study on the implementation of carbon dioxide as a working fluid for a geothermal system. Additionally, the two-phase flow model was considered to simulate the performance of the proposed working fluid. It was illustrated that the utilization of carbon dioxide instead of water can result in higher heat extraction. Another study regarding this issue was conducted by Wang et al⁵² in 2019. Moreover, water and isobutene were recommended as two working fluid for the geothermal system, and a parametric study on key parameters such as flow rate, well length, and wellbore size was performed. The results indicated that the generated power for water and isobutene can be reached to 143.5 and 258.1 kW, respectively. Furthermore, Wang et al⁵³ in 2019 presented a model to evaluate the supercritical carbon dioxide as working fluid for a geothermal system. In addition, the thermodynamic performance of the proposed system was investigated. For this reason, the key parameters were introduced as flow rate, evaporation temperature, supercritical temperature, and pressure. Finally, the results of new fluid utilization were compared with typical refrigerant fluids such as R600a, R152a, R142b, R236ea, and etc.

Additionally, the prospective aspects of small geothermal power plants to exploit geothermal reservoirs

with medium and low temperatures have been investigated by Franco and Vaccaro.⁵⁴ As they indicated, the most crucial element contributed to a geothermal power plant's design with medium temperatures can be mentioned as its size, due to its influence on the lifetime of the reservoir, the durability, and the economic planning of the power plant. Also, with combining investigations on economic aspects with novel approaches of efficiency improvement, the sustainability associated with geothermal power plants, which have small sizes, is achievable.

Furthermore, the most significant element in the prospective improvement in a geothermal power plant can be considered as reducing the costs associated with installation and drilling of facilities, as well as augmenting the efficiency. Due to the requirement of further funds for improving efficiency, it is crucial to discover methods with high efficiency which have the minimum cost. For the sake of setting up a sufficient harmony between plant wastefulness or energy loss and economic costs, they presented their approach which combines economic and the energy-related aspects of work. The utilization of this approach can be mentioned as preproject decision making and preparation, as well as comparing various kinds of geothermal power plants with a regular base and selecting distinct geothermal choices like organic Rankine cycle (ORC) or immediate steam. So, with the help of this approach, the determination of the plant size regarding the volume of a reservoir and other constraints can be provided; therefore, an efficient and sustainable design can be generated.

It is acclaimed by Feili et al⁵⁵ which renewable energies perform as a crucial part in the transition to an environmental-friendly economy by presenting a reliable supply of energy. In this paper, it is mentioned that a cost-effective energy source with a great worldwide demand is geothermal energy; however, plenty of geothermal power plants confront possible problems and failures which coerce the improvement of an extensive method for dealing with these issues. Additionally, the utilization of Failure Mode and Effects Analysis (FMEA) to evaluate regular problems in geothermal power plants was neglected. Also, for determining, classifying, and evaluating these issues, FMEA can be regarded as a satisfactory method. Five main components associated with a geothermal power plant have been investigated for determining a favorable procedure to develop the plant and to enhance its reliability by proposing special corrective operations for each issue. Furthermore, for evaluating the issues contributed to geothermal power plants and determining the severity, risk, and repetition cycle of these issues and establishing priority for them accordingly, FMEA has been utilized.

3 | HYDROGEN PRODUCTION SYSTEM

During the past years, a great number of researchers have been focused on hydrogen and regarded it as the future energy in the world.^{13,25,26,56,57} The overall cost associated with total hydrogen production relies on production, liquefaction, storage, and distribution costs.⁵⁸ Currently, the amount of producing hydrogen is relatively 9 billion kilograms annually. The utilizations associated with more than 95% of hydrogen include industrial application in the electronics, metals, and other related industries. The connection between renewable electricity generation and transportation, both portable and stationary demands of energy, is provided by hydrogen.⁵⁹⁻⁶¹ On the condition of using the electricity from wind, geothermal, and other renewable sources for producing and storing hydrogen, the renewable energy energies are more reliable and can support a range of demands.⁵ In transportation section, hydrogen presents a path for transmitting renewable energies to fuel required for vehicles.⁶²

There are different approaches for producing hydrogen which some of them contain reforming of steam methane, electrolysis, gasification of coal, liquid thermochemical water-splitting, photo-biological, and photo-electrochemical. While the first three approaches are presently applied, the rest are still being progressed or researched. These approaches might need electrical energy and/or thermal inputs.⁶³ Electrolysis is used in plenty of existing and designed plans, although it can be enumerated as a process which is energy-intensive, for hydrogen production. Nonetheless, a perfect path for generating hydrogen from renewable energy, which is carbon-free, can be provided by this approach.⁶⁴ Here, the most common and partly commercial procedures of hydrogen production are depicted in Figure 6.

3.1 | H₂ production by using fossil fuels

Currently, reforming of hydrocarbon and pyrolysis are the two predominant pathways among different hydrogen production technologies from fossil fuel resources. Approximately, these technologies supplied most of the required hydrogen demand. Since their production technology is mature and their widespread exploitation. Today's required hydrogen is generated totally from fossil resources including 48% from natural gas, 30% from heavy oils and naphtha, and 18% from coal.⁶⁵⁻⁶⁷ Due to the significant importance of production costs and availability on fuel prices, fossil fuels hold on to be the influential source for world hydrogen generation.

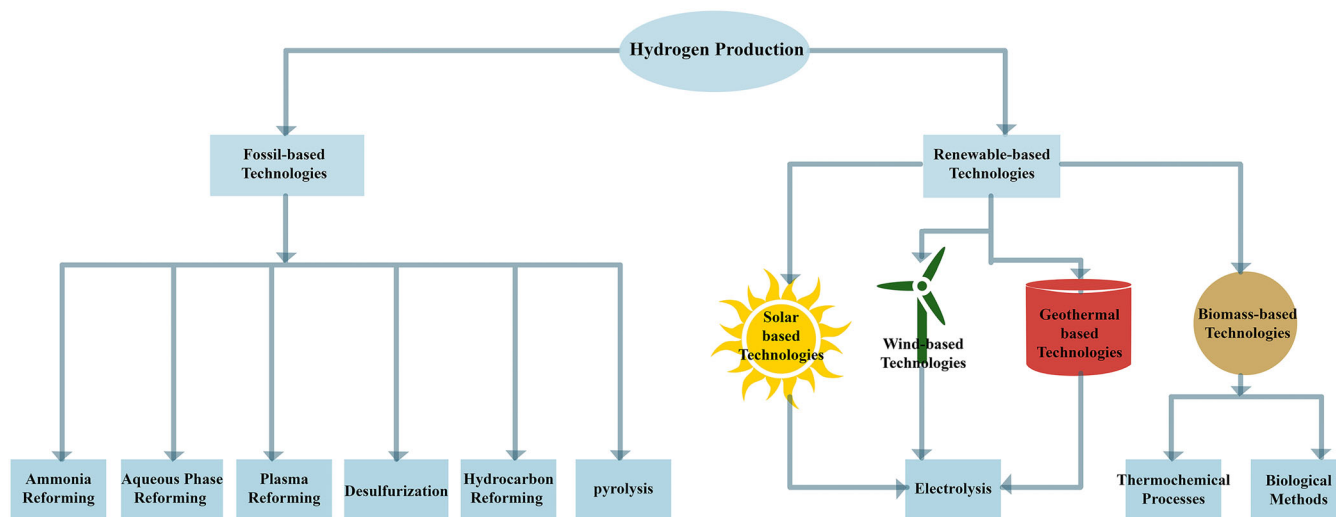


FIGURE 6 The most conventional routes for hydrogen production [Colour figure can be viewed at wileyonlinelibrary.com]

Likewise, other chemical and biochemical-related industries utilizing membrane reactors represent new initiative for producing H_2 from conventional fuels. A structure which is driven mass transfer on a specific driving force gradients such as temperature, pressure, concentration, and electric potential. Also, its thickness is normally much less than the membrane sides.⁶⁸ Five kinds of ideal continuous streams utilized in membrane-based separations are depicted in Figure 7. By considering the separation regime, three kinds of dense, porous and ion exchange can be mentioned as the membrane categorization. Based on their essence, synthetic and biological membranes are the two main types, which they are considered inorganic (ceramic or metallic) and organic (polymer), respectively. An appropriate membrane for utilizing in hydrogen production reactors should have

specific characterizations such as high hydrogen selectivity, high permeability to work with high flows and limited surfaces, and appropriate structural and chemical stability. Hence, the required parts for a composite membrane should (porous) support permitting the gases crossing, in combination with a barrier confining the interdiffusion in the support which is made of metal.⁷⁰ Figure 8 shows the conventional geometries of tubular and planar membranes.

3.1.1 | Hydrocarbon reforming approaches

Hydrocarbon reforming is defined as the conversion of hydrocarbon fuel into hydrogen via some reforming

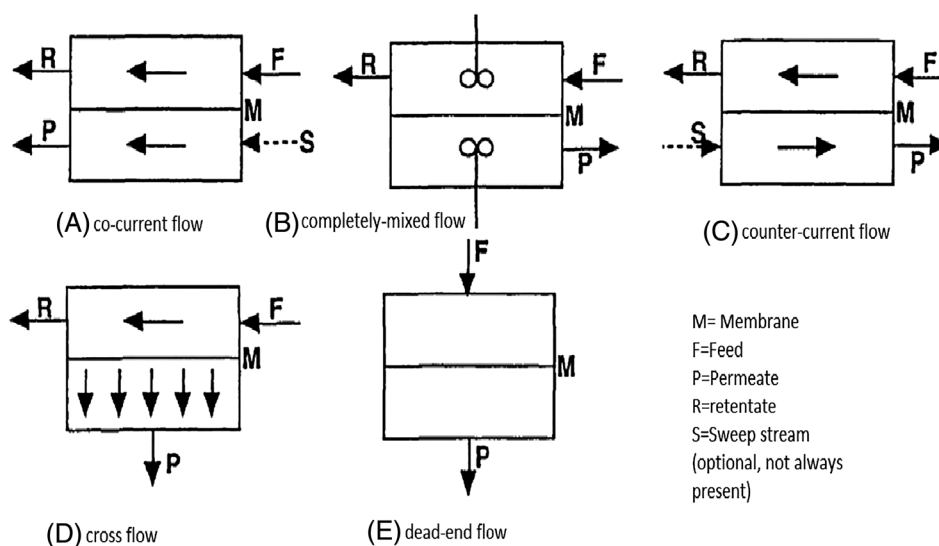


FIGURE 7 Kinds of ideal continuous flows utilized in membrane-based separations⁶⁹

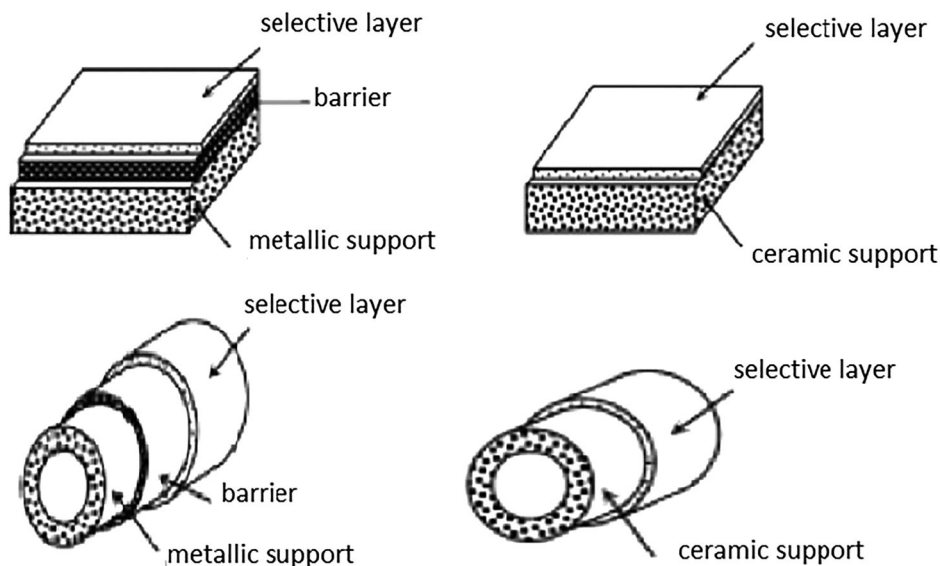
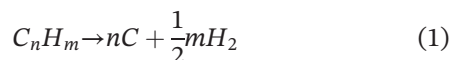


FIGURE 8 Composite membranes with tubular and planar geometries⁷⁰

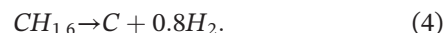
techniques. Beside hydrocarbon, steam or oxygen are the other reactants which can be used in the reforming process; afterwards, the endothermic reaction is entitled as steam reforming, or if oxygen is exploited, now the exothermic reaction is called as partial oxidation. The auto-thermal reaction happens when these two reactions are combined.⁷¹ A conventional reforming plant includes units such as the desulphurization section, the reforming and clean-up units, and the auxiliary components including compressor, pumps, heat exchangers, expander, combustor, and coolers.⁷²

3.1.2 | Hydrocarbon pyrolysis

Hydrocarbon (CHs) pyrolysis is a noted procedure in which the hydrocarbon as the hydrogen source thermally decomposed through the following general reaction:



Thermo-catalytic decomposition of light liquid hydrocarbons (which have boiling point in the range of 50°C–200°C), is conducted with the generating of elemental carbon and hydrogen, while in heavy liquid hydrocarbons (which have boiling point more than 350°C), hydrogen production occurs in a two-step procedure: hydrogasification and cracking of methane⁷³:



4 | H₂ PRODUCTION FROM RENEWABLE SOURCES

It is true that hydrocarbons are the primary source used for H₂ production for the time being. However, increasing the integration of renewable technologies cannot be neglected. Depletion of the fossil fuels and greenhouse effect proceeds an increase in the portion of technologies associated with renewable energies in the close future, while in a long-term period, it is thought that the required hydrogen demand is supplied by means of renewable energy sources.^{74–77} Many procedures for H₂ production from renewable resources are developed so far. Some biomass-based hydrogen production technologies and water splitting methods are briefly represented in following.

Biomass is considered as a primary energy which can be founded on plant and animal material, eg, in wood, grass, animal stools, and municipal waste.^{78–81} Biomass arising from plants is an organic substance in which the energy of sunlight is harnessed in chemical bonds through photosynthesis.⁸² CO₂ is emitted by consuming biomass for producing energy; however, the CO₂ emission quantity equals to the energy which is preoccupied by organisms before they were utilized and in their lifetime.⁸³ Hydrogen is obtainable by using biomass via thermochemical and biological procedures. In comparison: the characteristics of biological methods can be enumerated as less energy intensive and environmentally

friendly, due to the mild operation condition; however, they lead to low production rates of hydrogen.⁶⁶ Nonetheless, the production time is much lower in thermochemical processes. Furthermore, by considering the economic and environmental impacts, the output yield of produced hydrogen with gasification can be a thriving choice.^{84,85}

Water is easy-accessed and limitless feedstocks on Earth which is considered as a promising source for the production of H_2 via water decomposition methods including thermolysis, electrolysis, and photoelectrolysis.^{86,87} In order to achieve the cleanest fuel which can be utilized by a human, the required input energy for water-splitting can be provided from renewable energy sources.

Alongside other renewable energy sources, solar energy can also be considered as another viable source to be utilized for hydrogen production. Khanmohammadi et al.⁸⁸ in 2019 presented a thermodynamic analysis on a solar system integrated with thermoelectric generator (TEG) in the interest of hydrogen production. Moreover, the system's waste heat was recovered to enhance the output power generation. The results indicated that not only the output power was increased by 14 kW compared with the conventional system, but the hydrogen production rate was improved by 16% as well. In another study in 2019, Chen et al.⁸⁹ presented a life cycle assessment (LCA) on a solar-driven power plant for hydrogen production. In that matter, the water gasification process from biomass resources was considered as the main process, and the required heat was provided from a heliostat field. Moreover, the SimaPro software was utilized to evaluate the environmental effects of the proposed system. The results illustrated that the environmental impact was decreased by 90% with the recommended solar system instead of using electrical preheater. Another solar-driven study for the sake of hydrogen production was conducted by Kaleibari et al.⁹⁰ in 2019. In that respect, a concentrated photovoltaic system (CPV) was numerically investigated. Moreover, a solid oxide electrolysis cell (SOEC) was proposed to utilize the generated heat from solar source. The results revealed that the solar-to-hydrogen efficiency can be reached to 36.5%.

5 | PRODUCING HYDROGEN BY UTILIZING GEOTHERMAL ENERGY

5.1 | Thermodynamic analysis

The utilization of renewable energy sources is increasing due to augmenting the dearth of fossil fuels and rising

their environmental impacts. Geothermal energy is found to be a possible solution compared with other types of renewable energies.⁹¹ With the help of geothermal energy, the electricity can be generated, and the thermal energy can be provided by an affordable and clean method. By considering it, the geothermal energy utilization contributed to hydrogen production can be a provable method to be efficient in the prospective hydrogen production. In this way, the evaluation of the hydrogen production potential with electrolysis from renewable energy sources has been provided by Posso et al.⁹² in Ecuador. They considered some of the renewable energies such as wind, solar photovoltaic, geothermal, and hydropower. The quantity of the generated hydrogen by utilizing a PEM electrolyzer, which has efficiency equal to 75%, is approximately 4.55×10^8 kg/year. Two distinct utilizations have been considered which can be enumerated as first: hydrogen uses associated with automotive transportation by substituting diesel and gasoline, and second: replacing firewood with hydrogen for rural energy. As indicated in the results, 44% and 65% of the imported diesel and gasoline can be replaced by hydrogen. Additionally, the replacement of firewood with hydrogen can be achieved in 20 provinces in rural areas.

Furthermore, an analysis of economic improvement and rivalry between fossil fuels and clean energy regarding developments in clean energy innovations and the products associated with them has been presented by Lee and Hung.⁹³ In order to illuminate the role of the solar, wind, geothermal, hydrogen fuel cell, tidal current, biohydrogen, and biodiesel, a model has been introduced. According to the results, the performance of wind, hydrogen fuel cell, and biohydrogen is considerably acceptable in the lack of external support. Thus, the biohydrogen and the fuel cell can play a significant role in obtaining an effortless transition path to clean energies. Furthermore, the hydrogen production methods based on geothermal energy, their technologies, and possible applications have been examined by Baltaa et al.⁹⁴ A high-temperature electrolysis (HTE) process which its input energy was achieved by geothermal energy has been considered as a case study. Moreover, to assess the system performance, a thermodynamic analysis has been performed. Based on the results, the exergy and energy efficiencies associated with the hydrogen production were 86% and 87%, respectively.

Furthermore, the utilization of geothermal resources for hydrogen liquefaction was evaluated by Kanoglu et al.⁹⁵ In order to analyze the process, three different models have been regarded which contain the geothermal power's utilization for liquefaction cycle, the utilization of absorption cooling system for gas precooling before its liquefaction, and a cogeneration system for

which both geothermal electricity heat for absorption system are applied. An investigation of energy, exergy, and exergoeconomic associated with the integration of the geothermal energy and HTE process has been presented by Kanoglu et al.⁹⁶ In this paper, the parameters including power, destruction of exergy, heat transfer, and exergy efficiencies have been measured. Additionally, a study of a PEM water electrolysis for hydrogen production, powered by geothermal energy based on energy and exergy evaluations, has been provided by Yilmaz et al.,⁹⁷ Figure 9. Also, four models for the utilization of geothermal energy for producing hydrogen has been developed by Kanoglu et al.,⁹⁸ Figure 10. They investigated the models based on the thermodynamic aspect and considered reversible and irreversible operations of the models.

On the other hand, a novel route for utilizing energy resources efficiently along to preserve the environment from such hazardous effect like global warming is to propose cogeneration systems. Cogeneration systems produce electricity as well as other worthwhile types of energy (eg, heat, hot water, potable water, hydrogen,

etc.) from a specific energy source.⁹⁹ Among various renewable energy sources, geothermal energy utilization has been investigated widely in producing hydrogen. Hydrogen can be produced from all or part of the generated power from a geothermal plant through an electrolysis unit. It has been predicted that geothermal hydrogen production has an indisputable influence on hydrogen production economy.¹⁰⁰ Many kinds of research have been done so far on employing geothermal energy for hydrogen production. For instance, Ratlamwala et al.¹⁰¹ introduced an integrated geothermal plant with multi flashes electrolyzer (one to five flashes). To perform a comparative evaluation, they presented three different statements for energy efficiency and exergy of the system. Their discoveries showed that as the geothermal and environmental temperature raised, higher energy and exergy efficiency will be achieved. It has been illustrated that the incorporation of an electrolyzer with five flashes stage will result in the most efficient option. Yilmaz et al.¹⁰² proposed seven models for geothermal hydrogen production through electrolysis system. It has been shown that lower hydrogen production cost and

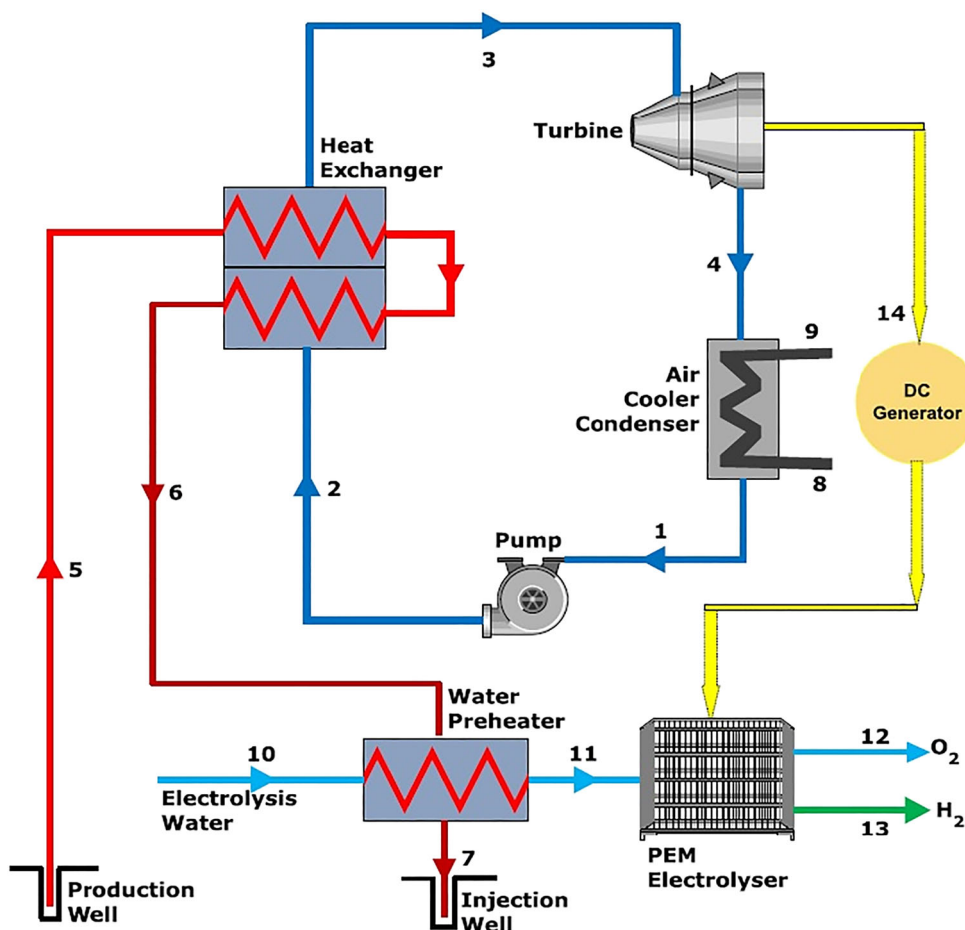


FIGURE 9 Production of hydrogen by using PEM electrolysis powered by geothermal source⁹⁷ [Colour figure can be viewed at wileyonlinelibrary.com]

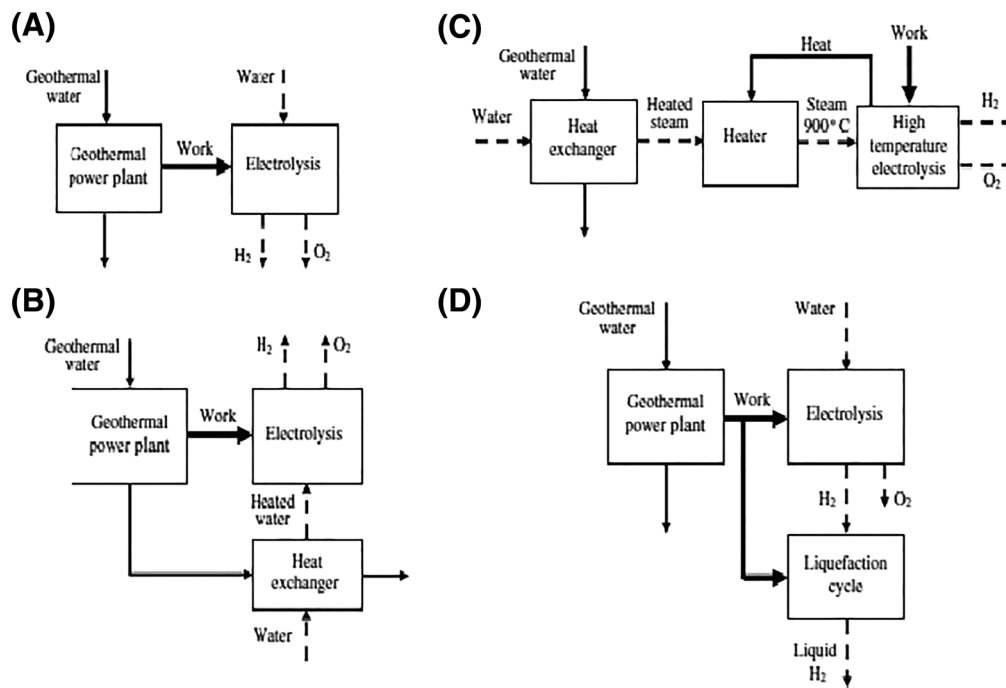


FIGURE 10 Four considered cases in hydrogen production with electrolysis by⁹⁸

liquidating process required a high geothermal temperature source. Also, Balta et al^{103,104} performed an energy and exergy analysis on a geothermal hydrogen production cycle. A four-step copper-chlorine thermochemical cycle has been simulated to generate hydrogen. The calculated energy and exergy efficiencies were equal to 21.67% and 19.35%, respectively. Yilmaz et al^{105,106} performed thermodynamic and exergoeconomic investigation on a geothermal and binary flash system connected to a water catalysis unit. Their results analysis demonstrated that the electricity exergetic costs and hydrogen production costs would be approximately about 11.1 \$/GJ (or 0.0400 \$/kWh) and 26.1 \$/GJ (or 3.14 \$/kg hydrogen), respectively. Balta et al¹⁰⁷ performed energy, exergy, and economic analyses on a geothermal-driven thermochemical copper-chlorine water catalysis system utilized for hydrogen production. It is illustrated that the hydrogen production cost considerably depends on the capacity of the plant and exergy efficiency. Gouareh et al¹⁰⁸ experimented hydrogen production by exploiting geothermal heat as an energy source and CO₂ as an operating fluid, regarding GIS analysis in Algeria. Based on the obtained results, Northeast and Southwest of Algeria have the most potential to perform this project.

Cai et al¹⁰⁹ researched on several optimization approaches for controlling renewable hydrogen production with the electrolyzer. Their approach ensured controlling the SOEC stack temperature and its local gradient temperature. A comparison has been done to assess the efficiency of the methods with each other, and the

obtained results were passable with literature. Balta et al^{103,104} studied on four selected potential approaches for geothermal hydrogen production. Their work was concentrated on raising the efficiency of the selected methods and showing the possibility potential method for low-temperature thermochemical hydrogen production cycles. It has been expressed that the copper-chlorine cycle is the most thriving cycle for geothermal-based production of hydrogen. Ouali et al¹¹⁰ have performed an investigation on hydrogen generation via hydrogen sulfide recovery plants in geothermal regions. The project purpose was designed to mark the different aspects of hydrogen generation from H₂S plants and the utilization possibility of such a procedure in Algeria's geothermal sources. Hydrogen production via hydrogen sulfide procedure was expressed to be economically and environmentally benign.

Ratlamwala et al¹¹¹ carried out a thermodynamic analysis to a novel multigeneration geothermal energy production plant including electricity, cooling, heating, hot water, and hydrogen. Based on their work findings, varying the geothermal temperature source from 440 to 500 K uplifts the daily hydrogen production amount from 1.85 to 11.67 kg. Akrami et al¹¹² have introduced a geothermal-based multicommodities production process. They have performed energetic, exergetic, and exergoeconomic analysis on the presented multigeneration system (MGS). As well as the assessment of the system performance, some parameters have been analyzed. The products units cost varies between 22.73 \$/GJ and 23.18 \$/GJ based on their investigation.

Bicer and Dincer¹¹³ proposed a multigeneration plant which is utilized a coupled energy supply design including a PV/T module (solar energy) and a geothermal well with 210°C. The presented energy conversion system is designed to produce electricity, heating, cooling, and hydrogen. Thermodynamic analysis assessment resulted in a maximum of 10.8% and 46.3% of the total energy efficiency and the total exergy efficiency, respectively.

Alzahrani et al¹¹⁴ presented, Figure 11, a multicommodity generation system consists of a supercritical carbon dioxide (SCO₂) Rankine cycle flowed by an ORC, an electrolyzer, and a heat recovery unit. This system was designed to produce hydrogen and power through a geothermal source which had a medium-to-high temperature, and provide space heating by utilizing the thermal energy. The energy and exergy efficiencies of the system were equal to 13.67% and 32.27%, respectively.

Also, a geothermal-based hydrogen production system has been studied by Balta et al⁹⁴ with the help of combining a geothermal source with a HTE process. Balta¹¹⁵ researched different geothermal-based hydrogen production systems and expressed that electrolytic hydrogen production is the most practical procedure to achieve high purity hydrogen. Hand⁶² analyzed a geothermal hydrogen production unit and simulated the influence of the variation of geothermal water on the thermodynamic performance of the system. It was reported that raising the

water temperature from 20°C to 80°C will result in a 17% improvement in electrolyzer efficiency.

Astolfi et al¹¹⁶ studied a solar-geothermal combination economically and declared that the solar-geothermal coupling could benefit lower electricity production cost. Suleman et al¹¹⁷ stated that solar-geothermal hybridization will raise some beneficial points such as lowering the difference between demand and supply, decreasing the life cycle emission and costing, and resulting in higher efficiency.

Ghaebi et al¹¹⁸ modified an ORC with a regenerative using different working fluids including R245fa, R114, R600, and R236fa, and a proton exchange membrane (PEM) electrolyzer for hydrogen generation. A comprehensive thermo-economic analysis is performed on the system performance. It is concluded from the analysis that R245fa obtained the maximum energy and exergy efficiency among the employed working fluids. In addition, it was the most cost-effective working fluid with 11.54 \$/GJ and 4.921 \$/GJ cost per exergy unit for generating power and hydrogen, respectively.

Yüksel and Öztürk¹¹⁹ studied that a nearly closed MGS consists of a geothermal source, an ORC, a Quadruple Effect Absorption Cooling System (QEACS), and a PEM electrolyzer to simultaneously produce electricity, heating, cooling, domestic hot water, and hydrogen. Their system was designed to drive the ORC and the

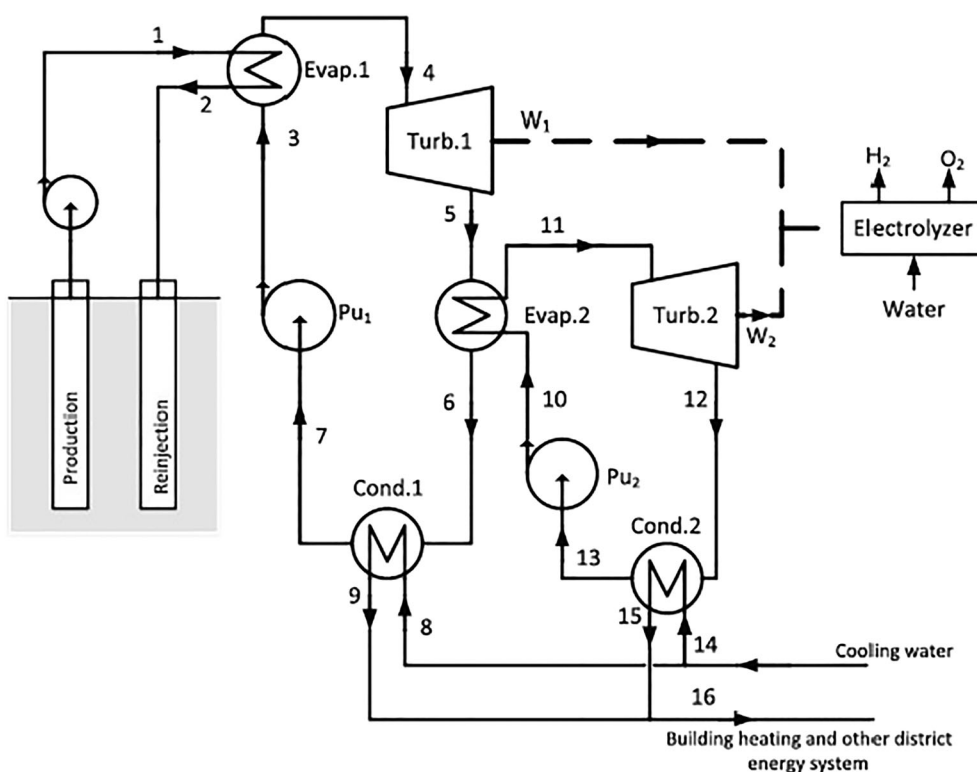


FIGURE 11 Schematic integrated system using by Alzahrani et al¹¹⁴

QEACS with the geothermal source and then employed in the PEM electrolyzer in order to hydrogen production. The PEM electrolyzer utilized the partial work of the ORC and also the waste heat of the geothermal source to preheat the inlet flow of the PEM electrolyzer. The authors investigated their system through thermodynamic and thermo-economic analysis. The thermodynamic assessment resulted in the overall energy efficiency and exergy efficiency of 47% and 32%, respectively. From their study, it is concluded that geothermal water temperature is a crucial parameter which affects the whole system performance and had an influence on the net power generation and also on the net total cost of the produced hydrogen.

Ganjesarabi et al¹²⁰ performed a thermodynamic evaluation on a Dora II geothermal power plant located in Turkey. The total energy efficiency and exergy efficiency of the system have been calculated to be 11% and 30%, respectively. Based on their environmental analysis, utilizing geothermal energy helps decrease the amount of greenhouses gases emissions.

Coskun et al¹²¹ have analyzed a geothermal-based multigeneration plant thermodynamically. Seven different conditions were defined for the system and studied under two working statuses: cooling and heating periods. It is illustrated in the results that energy and exergy efficiencies of the system were able to be uplifted by 3.4 and 1.1 times for cooling time and 4.2 and 1.2 times for heating time in case of comparing with a single power generation plant.

Al-Ali et al¹²² proposed that a novel multiproduction plant utilized geothermal energy source and parabolic solar collector technology. They have performed thermodynamic analysis on their presented system and compared it with a single-generation plant, cogeneration, and trigeneration plant. It is reported that multigeneration can raise the total energy efficiency of the system from 16% to near 80% and decrease the losses significantly. Also, it is shown that multigeneration concept is much more environmentally benign than single-generation plants.

Yuksel et al¹⁴ have studied on a novel integrated MGS which is driven by geothermal energy. The system is designed to supply power, hydrogen, oxygen, cooling, and hot domestic water. The integrated structure is composed of a geothermal source, a Kalina cycle, single effect absorption chiller, and hydrogen generation and storage system. From the thermodynamic analysis, it is found out that the reference temperature and geothermal flow temperature are the most important variables in the performance of the system. The whole system energy and exergy efficiencies have been reported as 42.6% and 48.2%, respectively.

Yuksel et al¹⁵ presented geothermal energy utilization in an integrated structure to produce hydrogen and other commodities. According to the developed thermodynamic model in their study, the energy efficiency and the exergy efficiency are calculated as 39.5% and 42.3%, respectively. Additionally, it is expressed that augmenting the pinch point and the turbine inlet pressure will decrease the system performance.

Cakici et al¹²³ simulated a combination of parabolic solar trough collector and a geothermal well and assessed the system performance through thermodynamic laws. Arslan and Kose¹²⁴ have shown that geothermal energy integration with other energy conversion systems has higher advantages than other renewable energy sources. Nikolaidis and Poulikkas¹²⁵ have done a review study on renewable-based hydrogen production. Supercritical water gasification of biomass is found to be the appropriate hydrogen production process in terms of economic considerations. Among renewable-based hydrogen production methods, geothermal energy offers a relatively cheaper procedure.

Shokati et al¹²⁶ have made a comparison between ORC and Kalina cycle in a geothermal plant. Based on their study, Kalina cycle had higher efficiency (4% more) and produces more net power (12% more). Calise et al¹²⁷ coupled solar energy and geothermal energy to develop a novel MGS. For supplying electricity, heating, cooling, and fresh water for a small residential, the system has been designed. The total energy and exergy efficiencies of the system have been reported as 54.7% and 46.4%, respectively.

Yilmaz¹²⁸ carried out a thermo-economic optimization using genetic algorithm (GA) over a MGS consisting of an alkaline water electrolysis unit for hydrogen generation and a combined flash-binary geothermal plant for supplying the required electrolysis electricity. The optimization was performed for minimizing the unit costs of the products: hydrogen, and electricity. The optimal exergetic efficiency is considered through optimization procedure and optimized each component in an isolated manner from the other components. Through the optimization process, the thermo-economic values of the system improved about 7.5%.

Boyaghchi and Nazer¹²⁹ have performed a comprehensive thermodynamic, economic, and environmental study on a sextuple energy conversion system which is driven through concentrating photovoltaic thermal collectors and a geothermal source. The system is composed of an ORC, PEM electrolyzer, and date dryer unit. The designed system provides electricity, cooling and heating effects, hydrogen, oxygen, and dried date productions. It is illustrated that the current density of PEM electrolyzer has influenced the cost of product lower than other parameters.

Anifantis et al¹³⁰ investigated a small-scale renewable-based energy conversion system for greenhouse heating. The proposed system is made of photovoltaic modules connected to an electrolyzer which produced hydrogen during the day and stores it in a storage tank to surmount the intermittency of the solar energy. During nights, hydrogen is converted to electricity in the electrolyzer and fed a ground source geothermal heat pump to supply the required heat. The total energy efficiency of the system is obtained to be about 11%. Caliskan et al¹³¹ presented a renewable-based cogeneration system to produce hydrogen and electricity. In this system, renewable energies such as wind, solar, and geothermal are utilized. The authors investigated the effect of different reference temperatures on exergetic investigations. It is depicted that total system efficiency is directly in relation to the selected reference temperature.

Akrami et al¹³² have evaluated a novel MGS (power, hydrogen, cooling, and hot water) which is driven by geothermal energy through thermodynamic analysis. The total energy and exergy efficiencies of the system for the considered operating conditions are reported as 34% and 43.6%, respectively. Exergy analysis showed that the heat recovery steam generator had the highest exergy destruction rated with 16.6%. The presented system could supply the following outputs: 816.7-kW net electrical power, 7.06 kg/s hot water, 1896-kW cooling capacity, and 0.05 g/s hydrogen production.

Parikhani et al¹³³ in 2019 presented an innovative MGS to provide heating, cooling, and hydrogen production. Moreover, the GA was applied to improve the system's performance through single and multiobjective optimizations. The results revealed that the thermal and the exergy efficiency would be 62.74% and 33.82%, respectively. Another study on multigeneration was performed by Nami et al¹³⁴ in 2018 including a geothermal system, methanol synthesis unit, and PEM electrolyzer. The proposed system was claimed to produce zero emission power using s-Graz cycle to eliminate the carbon dioxide emissions. Furthermore, the exergy and exergy efficiencies were evaluated to be 14.7% and 42.43%, respectively.

Gholamian et al¹³⁵ investigated the performance of the ORC on a geothermal-based system including a PEM electrolyzer and a TEG. In addition, three configurations were proposed, and the exergy and energy efficiencies were evaluated. Moreover, an optimization evaluation using GA was utilized to accentuate the performance of the proposed system.

Cao et al¹³⁶ in 2018 studied a geothermal-driven system to produce hydrogen from a combined cooling and power system. In that matter, several processes were employed including a geothermal flash cycle, kalinian cycle, and ammonia-water refrigeration cycle.

Consequently, a mathematical model was introduced, and the exergy analysis and the optimization evaluation were performed; the results indicated that the exergy efficiency can be increased to 26.25%.

Rostamzadeh et al¹³⁷ presented a thermodynamic analysis of a hybrid renewable energy system. The recommended system employed a hybrid biogas-geothermal heat source to provide heating and cooling as well as the production of hydrogen and freshwater. Further investigation including a parametric study was implemented to examine the overall performance of the system, and the exergy efficiency for each component was reported.

Kianfard et al¹³⁸ in 2018 studied a geothermal-driven MGS to produce hydrogen and water. The presented system included a combination of PEM electrolyzer and reverse osmosis (RO) unit. The impact of ORC on the system was investigated, and the exergoeconomic analysis was applied to evaluate the system's performance. The results demonstrated that the exergy costs for geothermal water and hydrogen production are 1.3\$/GJ and 4.257\$/kg, respectively.

The production of hydrogen sulfide in geothermal power plants is inevitable which is crucially considered as an environmental threat. For this reason, some researcher attempted to overcome this issue and suggested proper solutions. In that matter, Karapkmz¹⁶ and Dincer conducted a numerical study to produce hydrogen from hydrogen sulfide in geothermal power plants. Moreover, a thermodynamic analysis was applied, and the energy and exergy efficiencies were reported.

Karakilcik et al¹³⁹ carried out an exergy analysis on a geothermal-driven chlor-alkali cell to produce hydrogen based on ORC. The proposed system included a steam power turbine, NaCl tank, a separator, and an air-cooled condenser. The results revealed that the maximum power and hydrogen generation were 3.9 MW and 21.1 kg/h, respectively.

Another study on combined geothermal-based MGS was conducted by Emadi et al¹⁴⁰ in 2018. In addition, the impact of various thermodynamic cycles such as Kalina and Stirling cycles was investigated to estimate the hydrogen production potential. Further parametric study resulted in the assessment of exergy efficiencies which is calculated to be 43%. Moreover, the generated power from Stirling, liquefied natural gas, and Kalina cycles were reported.

A thermos-economic analysis was carried out by Ganjehsarabi¹⁴¹ in 2018 on PEM electrolyzer integrated with ORC. A combination of butane, pentane, and isopentane was implemented as a working fluid for ORC to produce hydrogen. The results indicated that the optimal mixture composition includes 40% pentane and 60%

butane. Additionally, Karapekmez and Dincer¹⁴² presented a novel solar-geothermal-driven system for hydrogen production. The recommended system involved an absorption system, ORC, and a hydrogen production unit. The main objective of this study was to eliminate the hydrogen sulfide from the geothermal field. The overall performance of the system was assessed, and the maximum energy and exergy efficiency were reported to be 78.37% and 58.40%, respectively. Furthermore, Ebadollahi et al.¹⁴³ studied a geothermal-driven MGS containing ORC, LNG system, ejector refrigeration cycle, and a PEM electrolyzer. The proposed MGS was investigated as energy and exergy point of view, and the heating/cooling capacity and output power were calculated. In addition, the thermal and exergy efficiency of the system was introduced to be 38.33% and 28.91%, respectively.

5.2 | Techno-economic analysis

Regarding the hydrogen production systems based on geothermal energy, 16% of the work required for electrolysis, and 2% for liquefaction can be avoided. The geothermal heat's utilization in HTE procedure has been studied by Sigurvinssona et al.¹⁴⁴ This process contains heat exchangers as well as an electrolyses by using solid oxide fuel cell (SOFC) system which works inversely, generating hydrogen and oxygen instead of consumption. Also, a techno-economic optimization contributing to the upper heat exchanger network in the HTE process for hydrogen production has been conducted by Mansilla et al.¹⁴⁵ The required heat has been achieved by combining the process either to a geothermal source or to a high-temperature reactor. Ingason et al.¹⁴⁶ examined the most cost-effective methods for producing hydrogen with the help of electrolysis from water by utilizing electricity from hydro and geothermal energy sources. Also, a study of evaluating the potential of geothermal energy use for hydrogen production has been presented by Valdimar et al.¹⁴⁷ They studied the effect of using a HOT ELLY high-temperature steam electrolysis procedure performing in the temperature range of 800°C to 1000°C. As indicated in the results, the cost of hydrogen production can be reduced by relatively 19% with the help of using HOT ELLY process with geothermal steam at 200°C. An effortless way toward a prospective cost-effective hydrogen energy has been illustrated by Arnason et al.¹⁴⁸ in Iceland.

Liquefaction process with the help of geothermal energy and its thermodynamic and economic evaluations have been carried out by Yilmaz et al.¹⁰² The quantity of hydrogen production and liquefaction per unit of

geothermal water (based on its mass) and the cost of production and liquefaction a unit mass of hydrogen have been measured. The authors also examined the effect of geothermal water temperature on the related-cost of hydrogen production and liquefaction processes.

Boyaghchi and Safari¹⁴⁹ have performed a multiobjective optimization on a multigeneration geothermal-based plant. After optimization, it is reported that the exergy destruction rate and exergy cost rate can be lowered by three and five times, respectively, and a 17% improvement can be seen in the total cost than the base state.

Ahmadi et al.¹⁵⁰ investigated the techno-economic feasibility of hydrogen production from a binary geothermal power plant. Based on the reported results, higher geothermal temperatures lead to higher energy and exergy efficiencies of the total plant, respectively. In addition, economic analysis revealed that the hydrogen production cost and electricity cost have a linear relation. The authors also used GA to optimize the introduced process of hydrogen production.

Rahmouni et al.¹⁵¹ performed an environmental investigation on a geothermal-based hydrogen production process which is operated employing CO₂ as working fluid. It is reported that the proposed system is able to produce hydrogen 22 kg/h, with the 40 kg/s mass flow rate of CO₂ and 296 K. From economic consideration, the produced hydrogen is 8.24\$/kg H₂ which is far from the market price, but it can be more competitive by considering the carbon tax.

5.2.1 | Economics of hydrogen production

The price of the energy conversion system and the hydrogen generation plant are highly effective on the hydrogen production cost. The hydrogen production processes require energy in the form of thermal or electrical which are provided by energy conversion plants that comprise the largest share of overall hydrogen cost.¹⁵² Cost of electricity is considerably higher than thermal energy since it is inevitable for a power plant to accomplish thermal-to-power conversion. In that regard, the thermal energy-based methods are considered more economical. For this reason, the main interest of researches is to find alternatives to pure electrochemical water splitting. On the other hand, the quality of thermal energy arises another issue regarding material stabilities and high-temperature thermal energy availability. Pure thermal water splitting demands very high temperature. Additionally, achieving high efficiency of multistep water-splitting methods requires temperatures more than 726°C (>~1000 K) from current technologies. Even though this temperature range is accessible with the assistance of advanced solar

and nuclear conversion technologies, there are still progressing investigations regarding material compatibilities as well as other issues for middle-term and long-term electric energy input which are able to perform at moderate to low (<1000 K) maximum temperature. Even though hybrid cycles hydrogen generation methods are considered more expensive than pure water-splitting technologies, they are more profitable in comparison with pure electrochemical water splitting methods.

Various review papers elaborate on the cost of hydrogen generation from different energy sources with diverse generation technologies.^{7,153,154} The scientific and technological data of hydrogen generation method are utilized to predict the hydrogen cost from conventional and renewable resources.¹⁵⁵ However, the cost of hydrogen production from renewable energy resources is not considerably different from hydrogen cost using conventional methods, mainly, steam methane reforming. Pure electrochemical hydrogen production cost from hydro wind and tidal energy sources demonstrate similar price trends which vary from \$4.72 to \$6.08 per kg of hydrogen.¹⁵⁶ It has been suggested that the DOE price target for hydrogen production can be achieved with electricity prices less than \$0.02/kWh which is considered infeasible, even though geothermal-driven electricity production cost is approximately close to this target value. In addition, Schoots et al¹⁵⁷ revealed that compared with nuclear and fossil-based power production, the DOE price target is considered a long-term objective. The hydrogen production cost is highly dependent on the electricity cost especially for water electrolysis technologies which the electricity cost comprises the 85% share of total hydrogen production cost. Various parameters such as the location of the hydrogen generation plant, source of electricity generation, taxes, governmental promotions, and subsidies can alter the hydrogen production costs.¹⁵⁸ Levelized cost of electricity (LCOE) for various renewable energy sources are presented in Table 1 which are estimated in USD.¹⁵⁹ Table 2

Cost of geothermal-assisted hydrogen production

Geothermal power is considered as one of the economical renewable technologies with high capacities which are continuously available during a day despite other promising renewable energy resources (ie, wind and solar). Balta et al¹⁰⁷ conducted an economical investigation on geothermal-assisted Cu-Cl cycle. They revealed that despite high-temperature geothermal energy which is considered infeasible in most region, the heat upgrade—for example using mechanical heat pumps, chemical heat pumps, or electric heating—introduces novel alternative for hydrogen production from geothermal energy via hybrid thermochemical cycles which forces an additional cost (around ~\$1000/MWth) to the overall hydrogen cost. The results demonstrated that the hydrogen cost is \$2.05/kg for a daily production of 50 tons. Kanoglu et al⁹⁶ studied the potential of coupling HTSE to geothermal source and predicted that the hydrogen cost can be achieved by \$1.9/kg. The HTSE process requires high temperature which narrows down the number of suitable geothermal energy. Yilmaz et al¹⁰⁵ estimated the hydrogen cost of a geothermal-driven electrolysis plant. The results demonstrated that the hydrogen cost is \$2.26/kg which results in very low source-to-hydrogen efficiency. Moreover, Yilmaz¹²⁸ conducted a similar study with more efficient geothermal power plant, and the hydrogen cost was reported \$1.08/kg which is considered very economical considering the small scale of a power plant. Ramazankhani et al⁴⁵ presented a feasibility study of geothermal-based hydrogen production plant using conventional electrolysis and examined 14 different provinces in Iran. Khalid et al¹⁶⁰ investigated a geothermal-based poly-generation systems. The results revealed that the LCOE is \$0.089/kWh with a daily hydrogen production of 64 kg.

Furthermore, Figures 12 and 13 depict hydrogen production costs based on electrolysis and thermochemical process with various energy sources, respectively. As it can be observed, the geothermal-assisted hydrogen production cost based on electrolysis is competitively lower than other sources like wind, solar thermal coupled with natural gas, solar PV, and grid. Also, the same behavior can be seen for geothermal-assisted hydrogen production cost based on thermochemical process.

TABLE 1 LCOE for different energy sources

Source	Kind	LCOE (\$/kWh)
solar	PVs	0.085
	Thermal	0.242
Wind	Onshore	0.637
	Offshore	0.157
Geothermal		0.047
Biomass		0.102
Natural Gas	Combined Cycle	0.057

5.3 | Environmental aspect

5.3.1 | Environmental impacts of hydrogen production

One of the options which is presented for eliminating and decreasing the environmental impact of

TABLE 2 The literature review on previous investigations on geothermal-driven hydrogen production

Authors	Case study	Investigation method	Hydrogen production process	Results	Ref
Yuksel et al.	Geothermal	Thermodynamic analysis	PEM electrolyzer And kalina cycle	Overall energy and exergy efficiency calculated by 42.59% & 48.24%	14
Yuksel et al.	Geothermal system and single effect absorption cooling	Thermodynamic analysis	Electrolyzer and ORC cycle	Overall energy and exergy efficiency calculated by 39.46% & 44.27%	15
Hand	Geothermal system with Rankine cycle	Numerical study with Transys	Water-alkaline electrolyzer	Highest overall efficiency is reachable at H ₂ production rate of 4 m ³ /hr	62
Posso et al.	Solar photovoltaic, Wind, Geothermal and Hydropower	Comprehensive study	PEM electrolyzer	H ₂ production can reach 4.55*10 ⁸ kg/year	92
Lee & Huang	Wind ,Solar, Biodiesel and Geothermal	Comprehensive study	-	Forecasted output level by the 2040	93
Balta et al.	Geothermal	Thermodynamic analysis	High Temperature electrolysis	Overall energy and exergy efficiency calculated by 87% and 86 %	94
Sigurvinsson et al.	Geothermal	Techno-economic optimization	High Temperature electrolysis	Hydrogen production reaches 1.01*10 ³ kg/yr	144
Mansila et al.	Geothermal coupled with high-temperature reactor	Techno-economic optimization	High Temperature electrolysis	Optimized parameters were reported based on Genetic Algorithm	145
Ingason et al.	Geothermal and Hydro power	Optimization analysis	Electrolysis	Presented results for site selection and proper technology for H ₂ production	146
Valdimar et al.	Geothermal	Feasibility study	Hot Elly high temperature electrolysis	Hot elly process reduces the H ₂ production cost by 19%	147
Kanoglu et al.	Geothermal	Thermodynamic analysis	Liquefaction cycle	Three possible case were compared and result were reported	95
Kanoglu et al.	Geothermal	Exergoeconomic analysis	High temperature steam electrolysis	The consumption energy for H ₂ production is 133 kWh	96
Yilmaz et al.	Binary Geothermal	Thermodynamic analysis	Electrolysis with ORC cycle	Overall energy and exergy efficiency calculated by 11.4% and 45.1 %	97
Kanoglu et al.	Geothermal-driven binary cycle	Thermodynamic analysis	High temperature electrolysis	Highest second law efficiency reaches 37.2%	98
Yilmaz et al.	Geothermal	Economic analysis	Water electrolysis and pre-cooled Linde-Hampson cycle	Minimum hydrogen production cost was 0.979 \$/kg H ₂	102
Ratlamwala and Dincer	Multi flash Geothermal system	Thermodynamic analysis	electrolyzer	Overall energy and exergy efficiency calculated by 6.25% and 47.29 %	101
Balta et al.	Geothermal	Thermodynamic analysis	Four-step copper chlorine cycle	Overall energy and exergy efficiency calculated by 21.67% and 19.35 %	103
Balta et al.	Geothermal	Thermodynamic analysis	High temperature electrolysis and Cu-Cl cycle	Highest overall energy and exergy efficiency calculated by 51% and 65 %	104
Yilmaz et al.	Binary Geothermal	Thermodynamic analysis	PEM electrolyzer		105

(Continues)

TABLE 2 (Continued)

Authors	Case study	Investigation method	Hydrogen production process	Results	Ref
				Overall energy and exergy efficiency calculated by 6.7% and 23.8 %	
Yilmaz et al.	Binary Geothermal	Exergoeconomic analysis	Electrolyzer	Overall energy and exergy efficiency calculated by 46.6% and 45.8%	106
Balta et al.	Geothermal	Exergoeconomic analysis	Cu-Cl cycle	Overall energy and exergy efficiency calculated by 49% and 54%	107
Gouareh et al.	Geothermal	Comprehensive study	electrolysis	Most favorable location were introduced using GIS software	108
Ouali et al.	Geothermal	Literature study	Electrolysis using hydrogen sulfide	Hydrogen potential of Algeria	110
Ratlamwala et al.	Double flash Geothermal system	Thermodynamic analysis	electrolyzer	Hydrogen production rate can reach 11.67 kg/day	111
Akrami et al.	Geothermal	Exergoeconomic analysis	PEM electrolyzer with Rankine cycle	Overall energy and exergy efficiency calculated by 34.98% and 49.17%	112
Bicer and Dincer	Solar and Geothermal	Thermodynamic analysis	Electrolysis with Rankine cycle	Overall energy and exergy efficiency calculated by 10.8% and 46.3%	113
Alzahrani et al.	Geothermal system with CO ₂ as working fluid	Thermodynamic analysis	Electrolyzer with Rankine cycle	Overall energy and exergy efficiency calculated by 13.67% and 32.27%	114
Balta et al.	Geothermal	Thermodynamic analysis	High temperature electrolysis and Cu-Cl cycle	Overall energy and exergy efficiency calculated by 51% and 65%	115
Suleman et al.	Solar and Geothermal	Thermodynamic analysis	ORC cycle	Overall energy and exergy efficiency calculated by 54.7% and 76.4%	117
Ghaebi et al.	Geothermal	Exergoeconomic analysis	PEM electrolyzer	Overall energy and exergy efficiency calculated by 3.511% and 67.58%	118
Yuksel and Ozturk	Geothermal and absorption cooling system	Thermodynamic analysis	PEM electrolyzer	Overall energy and exergy efficiency calculated by 47.04% and 32.15%	119
Ganjehsarabi and Dincer	Dora II Geothermal	Thermodynamic analysis	ORC cycle	Overall energy and exergy efficiency calculated by 10.7% and 29.6%	120
Coskun and Dincer	Geothermal	Thermodynamic analysis	Rankine cycle	Overall energy and exergy efficiency increased by 3.40 and 1.12 times for cooling season and 4.25 and 1.25 times for heating season	121
Al-Ali and Dincer	Geothermal and Solar	Thermodynamic analysis	ORC cycle	Overall energy and exergy efficiency for multi generation systems was calculated by 78% and 36.6%	122
Boyaghchi and Safari	Geothermal	Optimization study	PEM electrolyzer	The optimization results were reported by NSGA II algorithm	149

(Continues)

TABLE 2 (Continued)

Authors	Case study	Investigation method	Hydrogen production process	Results	Ref
Cakici et al.	Parabolic solar trough and Geothermal	Thermodynamic analysis	ORC cycle	The exergy efficiency of ORC cycle was calculated by 45%	123
Calise et al.	Solar, Geothermal and Distillation unit	Exergoeconomic analysis	ORC cycle	The highest exergy efficiency was calculated by 50%	127
Ahmadi et al.	Binary cycle Geothermal	Thermo-economic analysis	PEM electrolyzer with Rankine cycle	The highest exergy efficiency was calculated by 37.99%	150
Boyaghchi and Nazer	Photovoltaic thermal and Geothermal	Thermodynamic analysis	PEM electrolyzer	The overall exergy efficiency increased by 2.12 times compared to specified basepoint	129
Anifantis et al.	Photovoltaic system and Geothermal	Experimental study	PEM electrolyzer	The overall energy efficiency was calculated by 40 %	130
Caliskan et al.	Geothermal, Solar and Wind	Thermodynamic analysis	PEM electrolyzer	The highest overall energy and exergy efficiency calculated by 3.44% and 5.865%	131
Akrami et al.	Geothermal	Thermodynamic analysis	PEM electrolyzer with ORC cycle	overall energy and exergy efficiency calculated by 33.92% and 43.59%	132
Rahmouni et al.	Geothermal with CO ₂ working fluid	Techno-economic analysis	Alkaline electrolyzer	The estimated cost of hydrogen production was calculated by 8.24 \$/kg	151
Parikhani et al.	Geothermal	Exergoeconomic analysis	PEM electrolyzer	The optimum thermal and exergy efficiency was calculated by 62.74% and 33.82%	133
Nami et al.	Geothermal and methanol synthesis unit	Thermodynamic analysis	PEM electrolyzer with S-Graz cycle	Overall energy and exergy efficiency calculated by 14.7% and 42.43%	134
Gholamian et al.	Geothermal and thermoelectric generator	Optimization study	PEM electrolyzer with ORC cycle	The exergy efficiency was calculated by 21.9% higher than proposed base case	135
Cao et al.	Geothermal flash cycle	Thermodynamic analysis	Electrolyzer with Kalina cycle	The highest exergy efficiency reached 26.25%	136
Rostamzadeh et al.	Biomass and Geothermal	Thermodynamic analysis	Kalina cycle	The overall thermal exergy efficiency was calculated by 62.28% and 74.9%	137
Kianfard et al.	Geothermal and RO desalination unit	Exergoeconomic analysis	PEM electrolyzer with ORC cycle	The hydrogen production cost was calculated by 4.257\$/kg	138
Karapekmez and Dincer	Geothermal	Thermodynamic analysis	PEM electrolyzer	The overall energy exergy efficiency was calculated by 27.8% and 57.1%	16
Karakilcik et al.	Geothermal	Thermodynamic analysis	Chole-Alkali cell with ORC cycle	The overall energy exergy efficiency was calculated by 6.2% and 22.4%	139
Emadi et al.	Geothermal	Thermodynamic analysis	PEM electrolyzer with Kalina and stirling cycle	The hydrogen production rate was calculated by 378.84 kg/hr	140
Ganjehsarabi et al.	Geothermal	Thermodynamic analysis	PEM electrolyzer with ORC cycle	The optimum composition of the proposed working fluid is 60% butane and 40% pentane	141
Karapekmez and Dincer	Geothermal and Solar	Thermodynamic analysis	electrolyzer with ORC cycle	The overall energy exergy efficiency was calculated by 82.9% and 83.4%	142
Ebadollahi et al.	Geothermal	Thermodynamic analysis	PEM electrolyzer with ORC cycle	The overall thermal and exergy efficiency was calculated by 38.33% and 28.91%	143

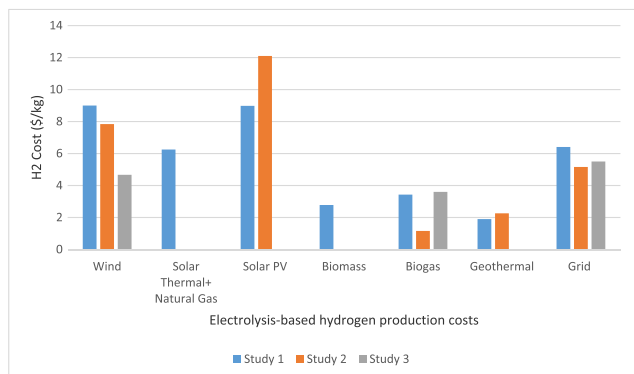


FIGURE 12 Hydrogen production costs based on electrolysis with various energy sources (data obtained from^{7,161-165}) [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

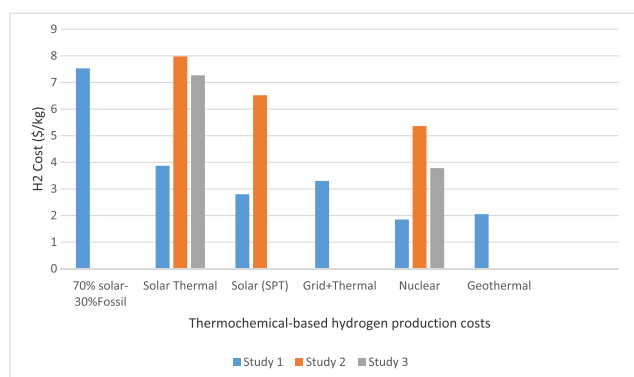


FIGURE 13 Hydrogen production costs based on thermochemical with various energy sources (data obtained from^{57,107,166-170}) [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

conventional fossil fuel is to replace and to consider hydrogen as a substitute. Although hydrogen consumption as a fuel is a clean option, producing it at high capacity and efficient distribution system needs modern technologies which have several side-effects during the production stages and construction steps.¹⁷¹ Several assessment methodologies have been applied so far on hydrogen production technologies. Life cycle assessment (LCA) is regarded as a practical approach to entirely determine the influence of a specific manufacture method on the environment.¹⁷² Major factors of global warming potential (GWP) and acidification potential (AP) are evaluated to measure the carbon dioxide pollutions and to measure the amount of waste products releasing to soil and water which specify the environmental effect of industrial technologies (eg, SO_x agents).¹⁷³ Several investigations have been presented so far which illustrates the advantages of utilizing renewable energies for hydrogen production over conventional fossil-based hydrogen production methods.^{67,174,175}

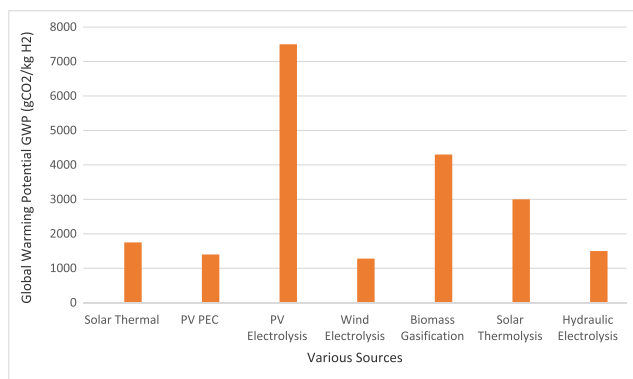
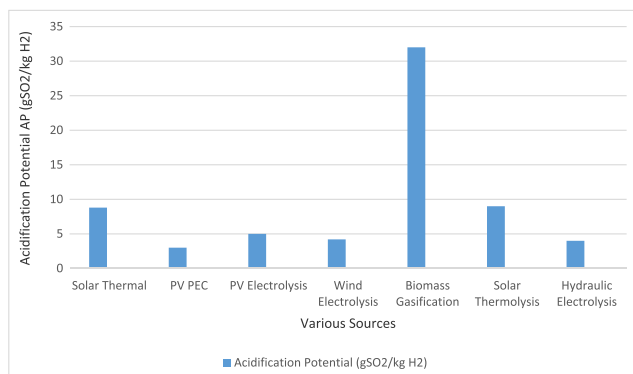


FIGURE 14 Acidification potential (AP) and global warming potential (GWP) of various hydrogen production sources (data obtained from¹⁵⁶) [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Comparative assessments illustrate that wind-based hydrogen production (produce electricity through wind turbines and use electrolyzers for hydrogen production) resulted in the least amount of carbon dioxide production while solar-PV-based hydrogen production generates the highest value of carbon dioxide.¹⁷⁶ Evans et al¹⁵⁶ compared carbon dioxide emission in geothermal hydrogen production with solar PV methods and reported that utilizing geothermal energy yielded two times more than the latter methods. In addition, it should be noted that materials which are used in the manufacture of PV modules are limited, and this issue has a direct effect on the overall LCA analysis of solar-PV-based hydrogen production. Pehnt et al¹⁷⁷ performed a survey to compare AP factor of some renewable-based hydrogen production technologies. Based on this investigation, construction of PVs has the most AP and GWP among studied methods. Following to PVs, geothermal, wind, and hydraulic energy are placed, respectively. It should be noted that there is a high demand of iron in wind-based and geothermal-based methods constructions. Rosner and Wagner¹⁷⁸ studied the AP and GWP of biomass-based and biogas-based hydrogen production methods and reported that these methods have similar GWP as wind-based hydrogen production methods. However, AP factor in these methods is more

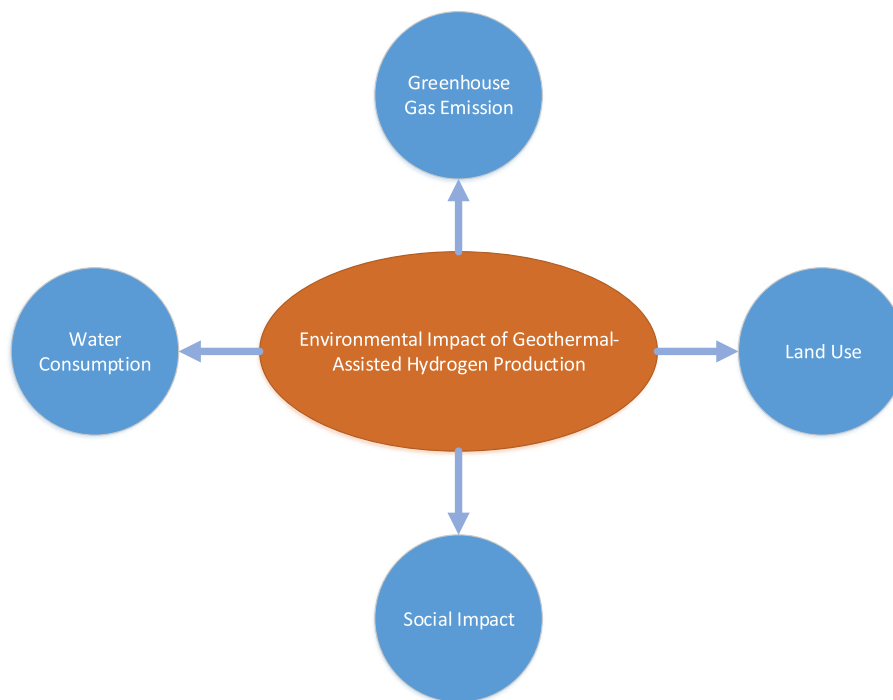


FIGURE 15 Summary of environmental impacts of geothermal-assisted hydrogen production [Colour figure can be viewed at wileyonlinelibrary.com]

than wind-based methods. Figure 14 demonstrates the total environmental impacts of studied hydrogen production technologies. It can be seen that the least environmental impact is obtained for wind-based electrolysis and nuclear-based thermochemical hydrogen generation methods. On the other hand, electrochemical hydrogen production methods, solar-based technologies, and geothermal-driven methods have the highest environmental impacts, respectively. However, it should be highlighted that renewable-based hydrogen production is totally more environmentally friendly than fossil-driven approaches. Making a comparison from source-to product, ie, source: renewable energies; product: hydrogen, illustrates that biomass gasification and PV-based hydrogen production technologies have the highest AP and GWP, respectively. From environmentalists outlook, wind-based electrolysis, hydraulic-based electrolysis, and photo-electrochemical (PEC) hydrogen production approaches are considered as the friendliest technologies for hydrogen generation. Figure 15

5.3.2 | Environmental impact of geothermal-assisted hydrogen production

Greenhouse gas emission

Technology selections are the most affected parameter in related emissions of utilizing geothermal energy. In this approach, the most portion of waste gases belongs to

carbon dioxide (over 90%),¹⁷⁹ so in case of direct release to the environment, the resulted hazardous emissions will be more than the standard value. Therefore, some technologies such as CO₂ capture, dry-ice production, or reinjection to geothermal wells are typically used in the modern geothermal power plants.¹⁸⁰

Land use

Surface footprint is fairly small in geothermal power plants since the main components of the plant are located underground.¹⁸¹ Therefore, the overall geothermal field is utilized in the footprint calculation, because of land subsidence's risk. A conventional geothermal footprint is calculated approximately in the range of 18 to 74 km²/TWh.¹⁸¹

Water consumption

A large volume of water is needed in geothermal power plants for cooling purposes.¹⁸² This amount can be managed by monitoring the overall reinjection of wastewater, nonevaporative cooling water, controlling the general pressure, and applying closed-loop recirculating layouts.¹⁸³ Based on the published comparison, production of wastewater in geothermal power plants is considerably more than conventional thermal power plants, approximately up to 300 kg/kWh.^{184,185}

Social impacts

Wastewater should be watchfully controlled since it can have harmful effects such as unpleasant smell of H₂S

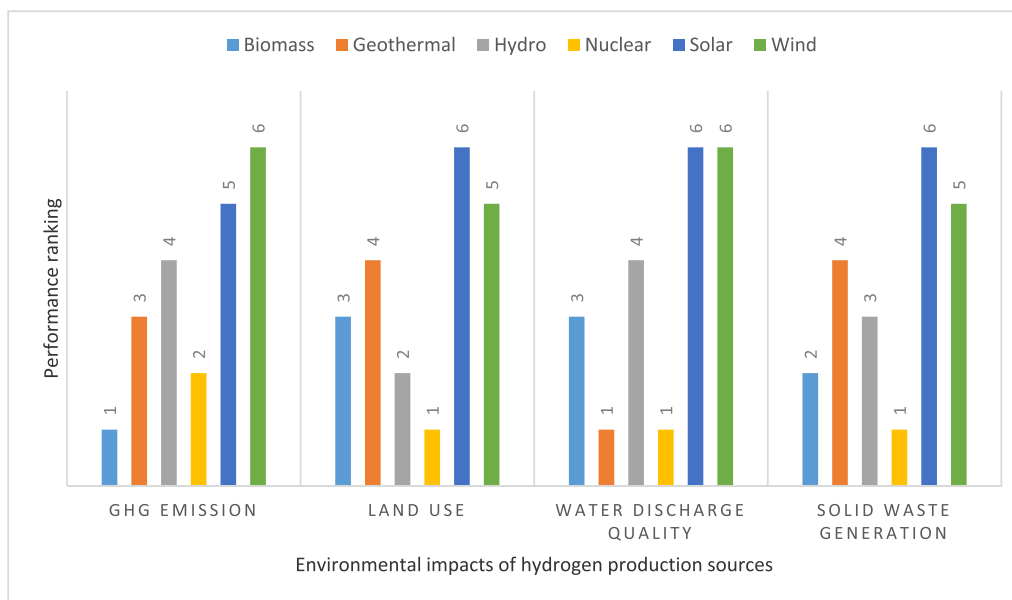


FIGURE 16 Environmental rankings of different hydrogen production sources (data obtained from²⁵) [Colour figure can be viewed at wileyonlinelibrary.com]

and wastewater polluted with hazardous materials including NH_3 , Hg, As, and B. These side effects of geothermal wastewater can be treated by utilizing a complete closed-loop cycle and reinjection of wastewater to the geothermal well.¹⁵⁶

5.3.3 | Summary of environmental impact

Environmental evaluation results of the studied hydrogen generation technologies from renewable sources are depicted in Figure 16. As indicated in the figure, the performance range is from 1 to 6 so that the best performance belongs to the ranking of 6 and the worst performance is related to 1. This comparative assessment expresses that wind-based hydrogen production is the friendliest technology based on GHG emissions. In addition, it can be seen that a significant attention should be considered for biomass-based hydrogen generation in order to decrease the amount of GHG emissions. Land use factor declares that solar-based systems are the best viable option, and on the other hand nuclear-based methods require the largest area since this method needs serious safety monitoring and significant control components in order to address cooling, solid waste, and pressure control issues. Comparison based on the quality of waste release illustrates that solar and wind have the minimum negative effect on clean water reserves in contrast to geothermal and nuclear plants. The drawback of geothermal plants is majorly for the risk of contamination of underground water sources. The disadvantage of nuclear power plants is caused as a direct discharge of

wastewater from cooling towers to nearby lakes and rivers which seriously affects the surroundings ecosystem. Based on solid waste generation comparison, solar-based technologies are considered as the cleanest environmentally friendly approach, while nuclear-based methods because of the radioactive intrinsic of the solid waste placed in the last ranking. An overall comparison states that solar systems are the cleanest methods and have the least negative impacts on the environment, and on the other hand nuclear-based approaches have the most hazardous environmental impacts. In conclusion, hydro-based methods due to the maturity of the technology and scaled-up feature gain the highest rank in the economic assessment. Wind-based hydrogen production is not an efficient hydrogen generation method. Geothermal-based hydrogen production have some serious negative limitations in case of social and technical aspects. On the contrary, solar-based and wind-based technologies placed on the highest social ranking due to the least hazardous impact on public health issue. On the other hand, it is forecasted that these two methods have considerable job opportunities in near future.

6 | CONCLUSION

Plenty of endeavors have focused on scientific research, technological development, and employment of modernization in hydrogen production. The usefulness of hydrogen production technologies relies primarily on innovations which exploit them more resourcefully on the condition of reducing adverse environmental impacts.

For this purpose, the aim of this article initially is to provide a concise summary of present and advancing hydrogen production technologies, and secondarily to present a comprehensive review of research associated with hydrogen production based on geothermal energy. As indicated in the mentioned research, the energy and exergy efficiencies are enhanced by using geothermal energy in the process of producing hydrogen. Additionally, environmental impacts associated with the production can be reduced significantly. Some crucial findings are itemized below:

1. As reported in the economic section, the costs of electrolysis and thermochemical-based hydrogen production by using geothermal energy are considerably low compared with other sources.
2. Based on the environmental impacts, comparative assessments illustrate that wind-based hydrogen production (produce electricity through wind turbines and use electrolyzers for hydrogen production) resulted in the least amount of carbon dioxide production, while solar-PV-based hydrogen production generates the highest value of carbon dioxide.
3. It can be seen that the least environmental impact is obtained for wind-based electrolysis generation method. On the other hand, electrochemical hydrogen production methods, solar-based technologies, and geothermal-driven methods have the highest environmental impacts, respectively. However, it should be highlighted that renewable-based hydrogen production is totally more environmentally friendly than fossil-driven approaches.

In summation, the thermodynamic, sustainability, and economic facets of hydrogen production systems and sources are the concentration of this study. In this way, some investigations focused on hydrogen production systems or their economic aspects or environmental impacts separately. Additionally, limited studies have been performed concentrating on technical, financial, social, and environmental facets of systems and sources needed for sustainable hydrogen production. This study can be considered as one of the first of its type by regarding the thermodynamic, techno-economic, and environmental impacts of hydrogen production sources for the objective of providing an extensive sustainability investigation of hydrogen production. Although the environmental impacts of geothermal-assisted hydrogen production are relatively low compared with other renewable energy sources, subsequent research must focus on reducing the environmental impacts of geothermal-driven methods. Also, hydrogen end-use options like various fuel cells can be mentioned as future studies for improving the sustainability analysis of hydrogen energy systems

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